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Augmented Reality-Assisted Bypass Surgery: Embracing Minimal Invasiveness

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Key words
- Augmented reality
- Extracranial-to-intracranial bypass surgery
- Image-guided surgery
- Minimal invasiveness
- Neuronavigation

Abbreviations and Acronyms
CT: Computed tomography
DSA: Digital subtraction angiography
EC-IC: Extracranial-to-intracranial
MCA: Middle cerebral artery
MRI: Magnetic resonance imaging
OA: Occipital artery
PICA: Posterior inferior cerebellar artery
STA: Superior temporal artery
3D: 3-dimensional

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■ OBJECTIVE: **The overlay of virtual images on the surgical field, defined as augmented reality, has been used for image guidance during various neurosurgical procedures. Although this technology could conceivably address certain inherent problems of extracranial-to-intracranial bypass procedures, this potential has not been explored to date. We evaluate the usefulness of an augmented reality-based setup, which could help in harvesting donor vessels through their precise localization in real-time, in performing tailored craniotomies, and in identifying preoperatively selected recipient vessels for the purpose of anastomosis.**

■ METHODS: **Our method was applied to 3 patients with Moya-Moya disease who underwent superficial temporal artery-to-middle cerebral artery anastomoses and 1 patient who underwent an occipital artery-to-posteroinferior cerebellar artery bypass because of a dissecting aneurysm of the vertebral artery. Patients' heads, skulls, and extracranial and intracranial vessels were segmented preoperatively from 3-dimensional image data sets (3-dimensional digital subtraction angiography, angio-magnetic resonance imaging, angio-computed tomography), and injected intraoperatively into the operating microscope's eyepiece for image guidance.**

■ RESULTS: **In each case, the described setup helped in precisely localizing donor and recipient vessels and in tailoring craniotomies to the injected images.**

■ CONCLUSIONS: **The presented system based on augmented reality can optimize the workflow of extracranial-to-intracranial bypass procedures by providing essential anatomical information, entirely integrated to the surgical field, and help to perform minimally invasive procedures.**

INTRODUCTION

Although a useful tool in the neurosurgeon's armamentarium, extracranial-to-intracranial (EC-IC) bypass surgery remains a demanding procedure in which the final result is dependent on the successful realization of several consecutive steps (8, 11, 19, 32, 34, 43). To begin with, the donor branch of the superior temporal artery (STA) (37) or the occipital artery (OA) (17) is harvested, after localization through manual palpation, with a Doppler ultrasound device or an angiographic road-map; a craniotomy is then performed centered over the region of interest. A suitable recipient artery is chosen (9), among those exposed, based on the vessel's caliber, its superficial localization, and the absence of significant branching; the donor and recipient vessels are then prepared, and only once all these steps are accomplished can the surgeon address the task of performing the anastomosis.

This lengthy procedure presents pitfalls (31, 34). Inadequate localization can result in damage to donor vessels during dissection, because of their variable anatomy and tortuous trajectory (1, 11, 17, 22, 23, 35). If the damage incurred precludes the vessel's use for anastomosis, a salvage operation must be performed, by harvesting a radial artery or a saphenous vein, which further lengthens the procedure; in the worst of cases, surgery may have to be aborted altogether. Furthermore, although current trends advocate minimal invasiveness (12), the craniotomy during theses procedures is usually performed large enough to increase the chance of finding a suitable recipient artery. In addition, the surgeon may have difficulty in intraoperatively identifying the optimal vessel that was chosen for anastomosis on preoperative angiography.

Augmented reality technology has found applications in surgery, where virtual images from preoperative imaging studies (e.g., computed tomography [CT] or magnetic resonance imaging [MRI]) are overlaid on the operating site for image-guidance (38). Various setups that use augmented reality have been reported for neurosurgical procedures (4-6, 14, 15, 18, 20, 21, 26-29, 39, 40), although none, to our knowledge, has explored its use for bypass surgery, where this technology might be helpful in overcoming the aforementioned difficulties.

We have previously developed a standard operating procedure, based on augmented reality with image injection into the microscope's eyepiece (5), and we sought to evaluate the usefulness of this setup during EC-IC bypass procedures.

METHODS

The augmented reality-based operating procedure we used has been detailed in a previous publication (5). For the purpose of this article, we briefly describe the procedure while emphasizing its specificities when applied to EC-IC bypass procedures.

Patients and Technique Assessment

Between November 2012 and July 2014, 3 female patients with Moya-Moya disease underwent STA-MCA bypass procedures, and 1 male patient underwent an OA-posterior inferior cerebellar artery (PICA) bypass with occlusion of the V3 segment of the vertebral artery, because of a dissecting vertebral artery aneurysm. In 2 of the STA-MCA bypass cases, both frontal and parietal branches were used for anastomosis. All procedures were performed in a hybrid neurointerventional suite equipped with a Flat-Panel system (Allura Xper FD20; Philips, Best, The Netherlands) allowing intraoperative 3-dimensional (3D) digital subtraction angiography (DSA) control of bypass patency. Patients with Moya-Moya disease were selected for revascularization after clear documentation of clinical progression and ischemic lesion observation on MRI, as well as demonstration of a loss of vascular reserve in the corresponding territory by either single-photon emission computed tomography or [^{15}O]water-positron emission tomography with acetazolamide challenge. After the procedure, patients underwent duplex ultrasonography during their hospital stay. Angio-MRI (with blood oxygen level-dependent CO_2 sequences) was performed at 3, 6, and 12 months for follow-up of graft patency and cerebral perfusion; in addition, single-photon emission computed tomography and/or [^{15}O]water-positron emission tomography was performed at 12 months in the patients with Moya-Moya disease.

The usefulness of augmented reality was assessed in each case through 3 Boolean parameters: Whether image injection helped in localizing the donor artery for harvesting; whether image injection helped to tailor the craniotomy; and whether image injection helped in unequivocally identifying the recipient vessel. Furthermore, manual palpation, Doppler ultrasound, and angiographic road-mapping are compared with augmented reality-assisted donor vessel localization: After drawing on the skin over the augmented donor vessel, we palpated the drawn trajectory for pulse perception. Doppler ultrasound was performed, and a radioscopy was performed with a radio-opaque rod placed on the drawn trajectory to evaluate its superposition on the angiographic road-map of the donor vessel. The size of craniotomies was also measured. Finally, the surgeon was asked at the end of each procedure whether he considered the image injection to have brought an added value to the surgery, that is, a value that would not have been present had image injection not been used, and whether he considered the setup disrupted the workflow.

The technique for anastomosis shall not be presented here, because dedicated descriptions are available in the literature (7, 8, 11, 32, 34, 43-45), and as it is not the goal of this report.

Preoperative Image Acquisition and Image Segmentation

All patients underwent a preoperative 3D DSA, with selective catheterization of both the external and internal carotid arteries. 3D angio-CT and 3D angio-MRI also were performed. These Digital Imaging And Communication In Medicine (i.e., DICOM) image data sets were loaded and fused for segmentation of the patient's skin, skull and vessels in a single 3D matrix (BrainLAB iPlan platform; BrainLAB, Feldkirchen, Germany). For patients undergoing a STA-MCA bypass, the STA and its branches were segmented, as well as the Sylvian vessels of interest; furthermore, the chosen point for anastomosis also was marked on this segmentation, after thorough study of the angiography. In the case of an OA-PICA bypass, the occipital artery, bilateral PICAs and the vertebral artery were selectively segmented. The aneurysm encountered in this patient also was segmented.

Patient and Operating Microscope Registration

After immobilization of the head in a radiolucent head-holder (Mayfield; Integra LifeScience, Plainsboro, New Jersey, USA), the patient was referenced to the navigation station (Kolibri; BrainLAB, Feldkirchen, Germany) relative to the neuronavigation reference star, using face surface-matching systems (Z-touch or Softouch, Kolibri; BrainLAB). The operating microscope (Zeiss Pentero 600 or 900; Zeiss, Oberkochen, Germany) was connected to the neuronavigation station and then calibrated to the neuronavigation reference star (Figure 1A and 1B).

Preincision Image Injection: Accuracy Control and Localization of Donor Vessels

Image injection into the microscope's eyepiece of 3D and 2-dimensional models of the patient's head were used to visually evaluate the accuracy of neuronavigation registration, by overlaying these models on the patient's *real* head (Figure 1C and 1D). If shift was observed, the mismatch was corrected by recalibrating the microscope upon the reference star. Once the accuracy of the augmented images was confirmed, image injection of the segmented donor vessel was used to localize it, and its course was drawn on the skin (Figure 2A and 3A).I Image injection of the recipient vessel and the chosen point of anastomosis was used for orientation.

Intraoperative Image Injection: Harvesting the Donor Vessels, Tailoring the Craniotomy, and Identification of Recipient Vessels

After skin incision, the segmentation of the donor vessel was used to guide harvesting (Figure 2B). When bony features at the skull's surface were exposed, image injection of the skull was used for a second accuracy control of neuronavigation registration. Image injection of the recipient vessel and the chosen point of anastomosis was used to help plan the craniotomy (Figure 3B). After the dura was opened, superposition of the injected segmentation of the recipient vessel was used for identification of the exposed vessel (Figure 3C and 4A); furthermore, it was used for a third control of neuronavigation accuracy. The preoperatively chosen point of anastomosis was used to indicate where this procedure should be performed (Figure 3C and 4A—C).

RESULTS

Usefulness of Augmented Reality

A total of 5 STA-MCA bypasses and 1 OA-PICA bypass was performed. The described setup allowed precise localization of the donor vessels in all cases; it helped to guide the skin incision and helped during harvesting by following the vessel and anticipating its course. It was particularly appreciated during dissection of the OA, because of its sinuous trajectory (Figure 2A—B). No damage incurred to the donor vessels. Table 1 summarizes for each case the comparison of augmented reality-